FORM PTO-1390 (REV. 5-93) U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE **TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371**	ATTORNEY'S DOCKET NUMBER **2345/158**
	U.S. APPLICATION NO. (If known, see 37 CFR 1.5) 09/890394

INTERNATIONAL APPLICATION NO.	INTERNATIONAL FILING DATE	PRIORITY DATE CLAIMED:
PCT/EP99/09845	**09 December 1999 (09.12.99)**	**29 January 1999 (29.01.99)**

TITLE
SENSOR AND METHOD FOR DETECTING CHANGES IN DISTANCE

APPLICANT(S) FOR DO/EO/US
Wolfgang DULTZ; Gisela DULTZ; Erna FRINS; and Heidrun SCHMITZER

Applicant(s) herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information

1. ☒ This is a **FIRST** submission of items concerning a filing under 35 U.S.C. 371.
2. ☐ This is a **SECOND** or **SUBSEQUENT** submission of items concerning a filing under 35 U.S.C. 371.
3. ☒ This is an express request to begin national examination procedures (35 U.S.C. 371(f)) immediately rather than delay examination until the expiration of the applicable time limit set in 35 U.S.C. 371(b) and PCT Articles 22 and 39(1).
4. ☒ A proper Demand for International Preliminary Examination was made by the 19th month from the earliest claimed priority date.
5. ☒ A copy of the International Application as filed (35 U.S.C. 371(c)(2))
   a. ☐ is transmitted herewith (required only if not transmitted by the International Bureau).
   b. ☒ has been transmitted by the International Bureau.
   c. ☐ is not required, as the application was filed in the United States Receiving Office (RO/US)
6. ☒ A translation of the International Application into English (35 U.S.C. 371(c)(2)).
7. ☒ Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. 371(c)(3))
   a. ☐ are transmitted herewith (required only if not transmitted by the International Bureau).
   b. ☐ have been transmitted by the International Bureau.
   c. ☐ have not been made; however, the time limit for making such amendments has NOT expired.
   d. ☒ have not been made and will not be made.
8. ☐ A translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).
9. ☒ An oath or declaration of the inventor(s) (35 U.S.C. 371(c)(4)). (UNSIGNED)
10. ☒ A translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371(c)(5)).

Items 11. to 16. below concern other document(s) or information included:

11. ☐ An Information Disclosure Statement under 37 CFR 1.97 and 1.98.
12. ☐ An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.
13. ☒ A **FIRST** preliminary amendment.
    ☐ A **SECOND** or **SUBSEQUENT** preliminary amendment.
14. ☒ A substitute specification and a marked up version of the substitute specification.
15. ☐ A change of power of attorney and/or address letter.
16. ☒ Other items or information: International Search Report; International Preliminary Examination Report; and Form PCT/RO/101.

Express Mail No.: EL244503846US

JC18 Rec'd PCT/PTO 30 JUL 2001

U.S. APPLICATION NO. (if known, see 37 CFR 1.5) 09/890394	INTERNATIONAL APPLICATION NO. PCT/EP99/09845	ATTORNEY'S DOCKET NUMBER 2345/158

17. ☒ The following fees are submitted:

Basic National Fee (37 CFR 1.492(a)(1)-(5)):

Search Report has been prepared by the EPO or JPO $860.00

International preliminary examination fee paid to USPTO (37 CFR 1.482) $690.00

No international preliminary examination fee paid to USPTO (37 CFR 1.482) but international search fee paid to USPTO (37 CFR 1.445(a)(2)) $710.00

Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO $1,000.00

International preliminary examination fee paid to USPTO (37 CFR 1.482) and all claims satisfied provisions of PCT Article 33(2)-(4) $100.00

				CALCULATIONS	PTO USE ONLY
ENTER APPROPRIATE BASIC FEE AMOUNT =				$ 860	
Surcharge of $130.00 for furnishing the oath or declaration later than ☐ 20 ☐ 30 months from the earliest claimed priority date (37 CFR 1.492(e)).				$	
Claims	Number Filed	Number Extra	Rate		
Total Claims	16 - 20 =	0	X $18.00	$0	
Independent Claims	2 - 3 =	0	X $80.00	$0	
Multiple dependent claim(s) (if applicable)			+ $270.00	$	
TOTAL OF ABOVE CALCULATIONS =				$860	
Reduction by 1/2 for filing by small entity, if applicable. Verified Small Entity statement must also be filed. (Note 37 CFR 1.9, 1.27, 1.28).				$	
SUBTOTAL =				$860	
Processing fee of $130.00 for furnishing the English translation later the ☐ 20 ☐ 30 months from the earliest claimed priority date (37 CFR 1.492(f)). +				$	
TOTAL NATIONAL FEE =				$860	
Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31). $40.00 per property +				$	
TOTAL FEES ENCLOSED =				$860	
				Amount to be refunded	$
				charged	$

a. ☐ A check in the amount of $__________ to cover the above fees is enclosed.

b. ☒ Please charge my Deposit Account No. 11-0600 in the amount of $860.00 to cover the above fees. A duplicate copy of this sheet is enclosed.

c. ☒ The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to Deposit Account No. 11-0600. A duplicate copy of this sheet is enclosed.

NOTE: Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137(a) or (b)) must be filed and granted to restore the application to pending status.

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Richard L Mayer (By Reg. No. 33,865 Darren C DED15??)
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Richard L. Mayer, Reg. No. 22,490
NAME

7/30/2001
DATE

[2345/158]

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant(s)	:	Wolfgang DULTZ et al.
Serial No.	:	To Be Assigned
Filed	:	Herewith
For	:	SENSOR AND METHOD FOR DETECTING CHANGES IN DISTANCE
Art Unit	:	To Be Assigned
Examiner	:	To Be Assigned

Assistant Commissioner
for Patents
Washington, D.C. 20231

PRELIMINARY AMENDMENT AND
37 C.F.R. § 1.125 SUBSTITUTE SPECIFICATION STATEMENT

SIR:

Please amend without prejudice the above-identified application before examination, as set forth below.

IN THE TITLE:

Please replace the title with the following:

--SENSOR AND METHOD FOR DETECTING CHANGES IN DISTANCE--.

IN THE SPECIFICATION AND ABSTRACT:

In accordance with 37 C.F.R. § 1.121(b)(3), a Substitute Specification (including the Abstract, but without claims) accompanies this response. It is respectfully requested that the Substitute Specification (including Abstract) be entered to replace the Specification of record.

Express Mail No.: EL244503846US

The Substitute Specification reflects the text of Revised Pages 1, 2, and 2a associated with the International Preliminary Examination Report.

<u>IN THE CLAIMS</u>:

Without prejudice, please cancel original claims 1 to 16 in the original application and substitute claims 1 to 14 from the Revised Pages, and please add new claims 17 to 32 as follows:

17. (New) A sensor for detecting a change in a distance between a first location and a second location, comprising:

at least one substantially helically coiled optical fiber for being mechanically connected to at least one of the first and second locations;

a light transmitter;

a detecting device for detecting optical signals and for generating an output signal dependent upon a polarization state of a first optical signal transmitted via the at least one substantially helically coiled optical fiber; and

a reference optical fiber path for simulating the at least one substantially helically coiled optical fiber and over which a second optical signal is transmittable;

wherein the first and second optical signals are detectable in one of (i) the detecting device and (ii) the detecting device and another detecting device, for determining any difference in polarization states of the first and second optical signals.

18. (New) The sensor of claim 17, wherein the detecting device is one of a polarimeter and a detector having a series-connected analyzer.

19. (New) The sensor of claim 17, wherein the at least one substantially helically coiled optical fiber is flexible in a helix direction and is for following changes in the distance between the first location and the second location.

20. (New) The sensor of claim 17, wherein the at least one substantially helically coiled optical fiber is joined to an elastic carrier material, which permits a change in form in response to mechanical loading of the at least one substantially helically coiled optical fiber,

and which retains the at least one substantially helically coiled optical fiber in an initial curved form in response to no mechanical loading.

21. (New) The sensor of claim 17, wherein the at least one substantially helically coiled optical fiber is wound around an at least one elongated carrier element.

22. (New) The sensor of claim 17, wherein the at least one substantially helically coiled optical fiber is secured to a carrier element so that the at least one substantially helically coiled optical fiber is movable in a wound form but remains stabilized on the carrier element.

23. (New) The sensor of claim 17, wherein one winding direction predominates in the at least one substantially helically coiled optical fiber.

24. (New) The sensor of claim 17, wherein at least one of the following is satisfied: the light source produces linearly polarized light; and a linear polarizer is situated at least one of on and at an input end of the at least one substantially helically coiled optical fiber.

25. (New) A method for detecting a change in a distance between a first location and a second location, the method comprising the steps of:

mechanically coupling at least one of the first and second locations to a substantially helically coiled optical fiber;

coupling an optical signal having a known polarization state into the substantially helically coiled optical fiber;

recording the optical signal transmitted over a connecting line for acquiring information pertaining to a polarization state of the optical signal;

determining the change in the distance from the information pertaining to the polarization state of the optical signal; and

comparing the polarization state of the optical signal transmitted with at least one of another polarization state of the optical signal before its transmission and a reference polarization state.

26. (New) The method of claim 25, wherein the step of determining the change in distance includes comparing a detected signal and at least one individual parameter of the detected

signal with a value determined in a calibration measurement corresponding to a specific distance.

27. (New) The method of claim 25, wherein the step of determining the change in the distance is performed using a detected signal, at least one individual parameter of the detected signal and a form of a three-dimensional curve of the substantially helically coiled optical fiber.

28. (New) The method of claim 25, wherein the reference polarization state is a polarization state of the optical signal determined following propagation of the optical signal through a communication link in a mechanical idle state.

29. (New) The method of claim 25, wherein the optical signal and a reference signal are detected.

30. (New) The method of claim 25, further comprising the steps of:

launching a linearly polarized light into the substantially helically coiled optical fiber; and

detecting a light having a defined linear polarization.

31. (New) The sensor of claim 21, wherein the at least one elongated carrier element is at least one of a cylinder and flexible.

32. (New) The sensor of claim 17, wherein the at least one substantially helically coiled optical fiber has only one winding direction.

REMARKS

This Preliminary Amendment cancels without prejudice original claims 1 to 16 and substitute claims 1 to 14 in the underlying PCT Application No. PCT/EP99/09845, and adds without prejudice new claims 17 to 32. The new claims conform the claims to U.S. Patent and Trademark Office rules and do not add new matter to the application.

In accordance with 37 C.F.R. § 1.121(b)(3), the Substitute Specification (including the Abstract, but without the claims) contains no new matter. The amendments

reflected in the Substitute Specification (including Abstract) are to conform the Specification and Abstract to U.S. Patent and Trademark Office rules or to correct informalities. As required by 37 C.F.R. § 1.121(b)(3)(iii) and § 1.125(b)(2), a Marked Up Version Of The Substitute Specification comparing the Specification of record and the Substitute Specification also accompanies this Preliminary Amendment. In the Marked Up Version, shading indicates added text and bracketing indicates deleted text. Approval and entry of the Substitute Specification (including Abstract) is respectfully requested. The Substitute Specification reflects the text of Revised Pages 1, 2, and 2a associated with the International Preliminary Examination Report.

The underlying PCT Application No. PCT/EP99/09845 includes an International Search Report, dated March 29, 2000. The Search Report includes a list of documents that were uncovered in the underlying PCT Application. A copy of the Search Report accompanies this Preliminary Amendment.

The underlying PCT Application No. PCT/EP99/09845 also includes an International Preliminary Examination Report, dated April 17, 2001, and an annex (including substitute claims 1 to 14 and the specification text of Revised Pages 1, 2, and 2a associated with the International Preliminary Examination Report). An English translation of the International Preliminary Examination Report and of the annex accompanies this Preliminary Amendment.

Applicants assert that the subject matter of the present application is new, non-obvious, and useful. Prompt consideration and allowance of the application are respectfully requested.

Respectfully Submitted,
KENYON & KENYON

Dated: 7/30/2001

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reflected in the Substitute Specification (including Abstract) are to conform the Specification and Abstract to U.S. Patent and Trademark Office rules or to correct informalities. As required by 37 C.F.R. § 1.121(b)(3)(iii) and § 1.125(b)(2), a Marked Up Version Of The Substitute Specification comparing the Specification of record and the Substitute Specification also accompanies this Preliminary Amendment. In the Marked Up Version, shading indicates added text and bracketing indicates deleted text. Approval and entry of the Substitute Specification (including Abstract) is respectfully requested. The Substitute Specification reflects the text of Revised Pages 1, 2, and 2a associated with the International Preliminary Examination Report.

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SENSOR AND METHOD FOR DETECTING CHANGES IN DISTANCE

[Field of the Invention
]FIELD OF THE INVENTION

The present invention relates to a sensor[, as well as to] and a method for detecting changes in the distance between a first and a second location[,] on the basis of optics.

[Background of]BACKGROUND INFORMATION
It is believed that the[Invention

Many]re are various methods[are known] for measuring changes in the distance between movable objects. For example, [one knows of]some methods may involve sensors, such as strain gauges, which are based on electrical methods. Changes in electric capacitance, as well as in magnetic flux are utilized when working with small changes in length. [The advantage of]When employing optical methods to determine linear variations[is that] there is no need for an electrically conductive connection between the points whose change in distance is to be measured. [Customary]There are interferometers for small and average distances of about 1 μm to 1 m, moiré systems, as well as transit-time measurements of light pulses. Interferometer systems may be very precise, but they [have the drawback of being mechanically]may also be extremely sensitive mechanically. Also, their operation entails substantial outlay for adjustments. For that reason, [they]it is believed that interferometer systems must be set up as substantially vibrationless systems, [so that]and they [are]may not be simple to use, especially for detecting changes in the distance between moving objects. [M]It is also believed that moiré systems are likewise precise, but, in a measuring range beyond a few centimeters, they [can]may only

be implemented at a considerable expense[; t]. Transit-time measurements of optical pulses and/or measurements of frequency shifts produced by the Doppler effect [are]may only be accurate for large distances and may require costly measuring electronics.

[

Object of the Invention

The object]

The reference "Berry's phase analysis of polarization rotation in helicoidal fibers", by F. Wassmann and A. Ankiewicz, Applied Optics, vol. 37, no. 18, June 1998, discusses a method for calculating the rotation of the polarization of light, which propagates through a helically wound optical fiber. The rotation of the polarization can be utilized for implementing an optical fiber sensor which can be used to determine the size of a displacement.

The reference "Two-dimensional HiBi fiber-optic coil strain sensor", by Y. Libo and A. Farhad, Acta Photonica Sinica, vol. 26, no. 7, July 1997, vol. 26, no. 7, pages 618-622, XP 000884999, discusses that with the aid of a wound optical fiber, to measure mechanical strains, the influence of the mechanical strain on the polarization state of the light is utilized, which propagates through the optical fiber.

The U.S. Patent No. 5,201,015 discusses a sensor for measuring mechanical strains with the aid of an optical fiber. The optical fiber has concentric windings. When a mechanical tensile stress is exerted on the sensor, the windings are elastically stretched, causing the peripheral path of the windings and, thus, also the optical path length of the light to increase in the optical fiber. The increase in the optical path length is utilized as a measure of the externally acting mechanical strain.

The U.S. Patent No. 4,389,090 discusses a device for producing specific polarization states of light in an optical fiber. At least one region of the optical fiber is formed as a winding or coil. The polarization state of the light can be adjusted and changed by varying the spatial orientation of the winding or coils, as well as by twisting the optical fiber.

SUMMARY OF THE INVENTION

An exemplary embodiment of the present invention is[, therefore,] directed to [provide]providing a sensor for detecting changes in distance[,] which is technically simple and inexpensive to implement, does not require any special mechanical stability, and which can be used to precisely determine small positional changes. A further object of an exemplary method of the present invention is to provide a method for detecting changes in distance which is simple to implement.

[Summary]Another exemplary embodiment of the [I]present invention[

The objective is achieved by] includes a sensor for detecting changes in the distance between a first and a second location[,] having at least one substantially helically coiled optical fiber, which is able to be mechanically connected to at least one of the locations, and having a light transmitter and a detector for optical signals. In this context, the detecting device is able to generate an output signal, which is dependent upon the polarization state of the optical signal transmitted via the optical fiber.[

Procedurally, the objective is achieved by] In addition, a reference optical fiber path is provided, which simulates the optical fiber and over which a second optical signal is transmitted, the optical signals transmitted over both paths being detected in a shared or in separate detecting devices so

as to enable differences in the polarization state to be determined.

Another exemplary embodiment of the present invention includes a method for detecting distance variations between a first and a second location, [having the following features]where:

a) mechanically coupling at least one location to a substantially helically coiled optical fiber;

b) coupling an optical signal having a known polarization state into the optical fiber;

c) recording the optical signal transmitted over the connecting line in order to acquire information pertaining to its polarization state;

d) determining the change in distance from the information on the polarization state of the transmitted signal[.

Advantageous embodiments of the sensor and of the method are characterized in the dependent claims 2 through 9 and 11 through 16, respectively.

The]; and

e) comparing the polarization state of the optical signal following the transmission to that prior to the transmission and/or to a reference polarization state.

Another exemplary embodiment of the present invention [is based on the principle of]involves the polarization of light changing in helically wound optical fibers in response to a change in the helical parameters. The polarization of the light at the output of a simple, helically coiled, optical fiber line is sensitive to movement, in particular to accordion-like movements of the fiber. This dependency of the polarization on the form of the three-dimensional[ ] (or non-planar) curve of the fiber can be used directly to measure the form, e.g., the length of the [accordion]accordion-like movements of the fiber windings. [Thus, t]The distance between any two locations can be determined by connecting them

using a movable, helically wound, elastic optical fiber line.

[T]In another exemplary embodiment of the [main reason for]present invention, the form dependency of the polarization state at the output end of an optical fiber is at least in part due to the considerable dependency of the fiber's optical activity upon the exact form of its helical windings. In the first approximation, this effect is achromatic and does not result in any polarization mode dispersion. It is believed to be caused by one of the so-called optical Berry phases, the spin redirection phase. This Berry phase or geometric phase is a phase effect produced by the structure of the fiber's space curve and not by a difference in the optical path length, as is the case with the normal dynamic phase of light. Nevertheless, geometric phases lead to the same interference effects of the light as do normal dynamic phases.

The size or magnitude of the spin redirection phase in a helically wound fiber [is equivalent]corresponds to the solid angle Ω that the k vector (k corresponds to the propagation constant β in the technical literature) wraps around on the sphere of the light-propagation orientations in the counter-clockwise direction when the light in the fiber is directed through a helical winding.

[For that reason]In another exemplary embodiment of the present invention,[it is important that] light [be]is coupled with a defined polarization state into the coiled optical fiber and [that]the transmitted optical signal [be]is detected [in a manner such]so that inferences can be drawn with respect to its polarization state or[ ]its individual polarization components after propagating through the optical fibers. From the change in the parameters of the optical signal prior to and following the transmission, or from a comparison to a reference from a calibration measurement or a concurrent reference measurement, inferences can be drawn with

respect to the form or the change in the form of the wound optical fiber and, thus, also with respect to changes in the distance between locations connected thereto.

[F]In another exemplary embodiment, for example, polarized light can be coupled into the fiber, and its polarization state or the strength of a specific polarization component can be measured[,] once it has propagated through the optical fiber[,] using a polarimeter or a detector having a series-connected or upstream analyzer. From knowledge of the polarizations or of individual polarization components prior to and subsequent to the transmission, conclusions can be drawn with respect to the change in polarization caused by the form and, thus, with respect to the deformation of the coils.

[If]In another exemplary embodiment of the present invention, if the transmission signal is compared to a reference, then precise knowledge of the polarization state prior to the transmission [is]may not [absolutely]be necessary. It [suffices]may be sufficient if a defined initial basic situation is always at hand. The reference is constituted, for example, of a series of measured values which were acquired during a calibration measurement using the optical fibers and which specify the output signal at specific distances between the first and second location. Alternatively, a reference signal can also be produced during the measurement in that a reference path, which [preferably]may simulate[s] the wound optical fiber, likewise receives a defined optical signal, and the two transmission signals are compared to one another. For this, they are either analyzed separately [and]and/or both intensities are compared to one another. The actual transmission signal can also be brought into interference[, however,] with the reference transmission signal and subsequently can be detected in a shared detector.

[The benefits provided by]Exemplary embodiments of the present

invention [of eliminating]can eliminate the need for specular surfaces or for a special mechanical stability of the system[,] are virtually universally applicable. The [ ]launching the optical signal into the fiber should, in fact, be mechanically stable, but it can be set up separately from the system to be measured. In addition, without entailing substantial technical outlay, the sensor can be assembled from individual, inexpensive components.

[Brief description of the drawing, whose figures show:
Figure 1 a sensor according to the present invention]BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a sensor having a helical optical fiber[;
Figure 2 a detail of] according to an exemplary embodiment of the present invention.

Figure 2 shows a helical optical fiber[;
Figure 3 a sensor] according to an exemplary embodiment of the present invention.

Figure 3 shows a sensor for measuring changes in the length of a telescope arm[.

Ways for Executing the Present Invention
] according to an exemplary embodiment of the present invention.

DETAILED DESCRIPTION

The lower part of Figure 1A shows a sensor according to an exemplary embodiment of the present invention having a helical optical fiber 1. [Here, t]The optical fiber has a fixed winding direction. [Generally, i]In the case of an arbitrarily bent fiber, it [suffices]may be sufficient when one winding direction predominates.

In addition, the optical fiber has a cladding which holds the

fiber in its helically bent form and is capable of elastically following movements, in particular those along the longitudinal axis of the coil. For this, the coils, as such, can also be embedded in an elastic substrate material, for example, in an elastic cylinder or the like.

The sensor also includes a light source 3, which [is preferably]may be a laser. Linearly polarized light emanating from light source 3 is launched into fiber coil 1. In the case that the light source does not emit fully polarized light, a polarizer P [is]can be positioned at the fiber input end to produce the defined polarization state. At the output end of the fiber coil, the polarization state of the transmitted optical signal [is]can be measured using a polarimeter 2. Alternatively, one can use a simple detector having a series-connected or upstream [ ]analyzer to measure the intensity of a defined polarization component.

Figure 1B schematically depicts a polarization ellipse to represent the polarization state of the light once it has propagated through the transmission route. X and y denote the vibration directions of the electric field vector. In the most general case, the field vector describes an ellipse having the main axes a and b, which is rotated by the angle φ in relation to the axes x and y.

[T]Exemplary embodiments of the present invention [utilizes]involve that the orientation angle φ of the polarization ellipse at the output end of the fiber path [is]being proportional to the so-called geometric phase introduced in the coil between the right-hand and left-hand circular component of the injected, linearly polarized light. Since the geometric phase changes with the coil shape, the orientation angle φ is a measure of and/or indicative of the coil shape. In this manner, the distance d between two points A1 and A2 can be measured on the coil and, thus, also the

distance and/or the change in the distance between two locations rigidly connected by points A1 and A2.

[In the special cases described in the following and elucidated on the basis of]Referring to Figure 2, the geometric spin redirection phase and, thus, the coil form can be determined quite simply. Each complete winding of the optical fiber on a cylinder Z of radius r, having pitch St, for which the lead angle Θ is the same at the beginning A and end E of the winding, produces a rotation φ of the injected, linearly polarized light. The angle of rotation φ is given by

(1) $$\varphi = \int_0^{2\pi} \left[1 - \cos\Theta(\Phi)\right] d\Phi$$

In this context, ϕ is the azimuth angle of cylinder Z; see Figure 2. For the case of a uniformly wound spiral, Θ is a constant, and one obtains:

(2) $$\varphi(\Theta = const.) = 2\pi(1 - \cos) \text{ and } \cos\Theta = \frac{\mathrm{St}}{\mathrm{L}}$$

Thus, if one couples [A]a linearly polarized light at angle α into the helix, then at the output end E, it has a polarization rotated by the angle φ thus α±φ. The operational sign of angle of rotation φ depends on the helicity of the coil or screw. L is the length of the fiber helix. At this point, in response to a change in pitch S[T]t of the helix, the helix or pitch angle Θ and, thus, the polarization direction at fiber end E change. If [one installs]a linear analyzer is installed at end E and then permits the light to strike a detector, then this registers an intensity I

(3) $I = I\cos^2[\gamma - (\alpha \pm \varphi)]$

whe[n]re γ is the orientation angle of the analyzer, and I_0 is the intensity of the linearly polarized light emerging from the fiber. The assumption here is that lossless conditions prevail and that the light in the fiber ideally remains linearly polarized.

For all other cases, I likewise depends on helix angle Θ and, thus, on the distance between points AE, although in complicated fashion. The correlation (or relation) may be[is preferably] determined through calibration or by measuring the parameters of equation (1), as well the various losses. At the detector, one obtains a signal which is dependent upon distance St to be measured and can be brought into a suitable measuring range by parameters r, γ and α.

It is believed that it is not necessary that only one single winding of the fiber may be used as a distance indicator. [It is likewise possible to use many windings]In another exemplary embodiment of the present invention, many windings can be used, as in Figure 1, as well as non-whole numbers of windings. In the case of an integral number of turns []or windings N between A and E and given the same helix angles at A and E, [it is possible to calculate]the angle of rotation φ may be calculated in accordance with equation (1), it being necessary to extend the upper integration limit to $2\pi N$. Given a number of turns N that is not whole and non-uniform windings, a calibration [is]may be more advantageous than the calculation, which can no longer be performed in accordance with the simple equation (1).

To fabricate a uniform coil form having constant helix angles, spindles are mounted at points A and E at the beginning and end of the winding about which the fiber can rotate freely with respect to angle Θ. These spindles are disposed perpendicularly to the cylinder axis of the winding. The fiber is mounted on an elastic carrier, which has a pivot at A and E

enabling it to rotate about the spindles. Since, in this case, the uniform helix adjusts itself automatically as a geodetic curve between points A and E on the cylinder, equation (3) can be applied for all pitches St of the helix, for whose formation the total length of the fiber suffices.

[Generally, a]An optical fiber does not always retain the [(]linear[)] polarization; i.e., when it emerges from the fiber, the light is no longer polarized as it originally was upon its entry into the fiber. This effect is produced, on the one hand, by deviations in the fiber core from circular symmetry and, on the other hand, by birefringence induced by the bending of the fiber. In so-called weakly birefringent fibers, which also feature a low polarization mode dispersion, an orientation distribution of the asymmetry of the fiber core is achieved in all spatial directions, for example, through rapid rotation of the preform when drawing the fibers. Therefore, fibers of this kind [are]may be especially suited for manufacturing a length-measuring [sensor]or distance-measuring sensor in accordance with the exemplary embodiments of the present invention.

To avoid stress-induced birefringence in the bent fiber, the bending radius of the fiber should not be too small. An estimation of the birefringence in bent fibers is given by L. Jeunhomme, Single-Mode Fiber Optics, N.Y. 1983, p. 60. It is [ideal]believed to be optimal when the wound fiber helix has a phase lag of less than $\lambda/10$, λ being the operating wavelength. On the other hand, even higher strain birefringence values [do]may not substantially interfere with the measuring principle, since, even in the case of elliptically polarized light at the output end of the fiber, the helix deformation causes changes in the orientation angle φ, which can be taken as a measure of the change in length. Large bending radii of the fibers can be achieved both by increasing the helix radius, as well as by enlarging the helical pitch.

A calibration of the sensor also includes changes in intensity in the detector at the fiber end, resulting from bending of the fiber in response to a change in the distance AE. A length measurement obtained by comparing the instantaneously measured values to values determined in a calibration measurement [is]may be advantageous for the practical application of the sensor, since [it makes it possible to eliminate]any influences on the polarization state of the light that are not caused by the change in the length of the wound optical fiber may be eliminated.

Figure 3 illustrates [one practical specific]an exemplary embodiment of the present invention. An elastic fiber carrier D, [for example]e.g., a steel, bronze or plastic wire, is provided with two mounting supports HA, HE, which can be fitted on spindles at A and E enabling them to freely rotate. [In the described example, t]The spindles at points A, E are connected to two tubes of a telescope arm, whose change in length needs to be measured. [In the described example, a]A helical optical fiber having one single winding is used, which is embedded in fiber carrier D.

Disposed upstream from holder HA is a light source LQ, which can also be mechanically connected to holder HA to assure stable coupling[ ] conditions. Light source LQ, which [preferably]may produce[s] linearly polarized light, is, [for example]e.g., a light-emitting diode or a semiconductor laser. The light is coupled via a lens L1 into the optical fiber, whose input end is positioned at holder HA. The fiber is secured on or in elastic fiber carrier D. In the case that the light source emits unpolarized light, linear polarizer PA must also be installed between the light source and the start of the fiber.

At the end E of the winding is holder HE, to which a lens L2 and the fixed or rotatable linear analyzer PE is secured. The

lens images light from the fiber onto detector DE. Light source LQ and detector DE are connected via easily movable electric conductors to corresponding network and recording devices N and R, respectively. To avoid interference effects, the light source, detector, and glass fiber are obscured in light-proof manner from the outside world.

[Industrial Applicability

The]The exemplary embodiments of the present invention [can]may be[advantageously] used in industrial applications to precisely detect changes in length and distance in a multiplicity of systems, such as in robot arms.

[

Abstract

The present invention is directed to a]

ABSTRACT OF THE DISCLOSURE

A sensor for detecting changes in the distance between a first and a second location, having at least one substantially helically coiled optical fiber, [which is able to]can be mechanically connected to at least one of the locations, and having a light transmitter and a detecting device for optical signals, the detecting device [being able to]can generate an output signal, which is dependent upon the polarization state of the optical signal transmitted via the optical fiber. [The present invention is also directed to a]A method for detecting the changes in distance between a first and a second location[, having] includes the following[features:]: mechanically coupling at least one of the locations[is mechanically coupled] to a substantially helically coiled optical fiber; launching an optical signal having a known polarization state[is launched] into the optical fiber; following transmission over the connecting line,[this][is detected in such a way] detecting this so that information is obtained with respect to its polarization state;[from this information,] and determining the change in distance [is determined]from this information.

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SENSOR AND METHOD FOR DETECTING CHANGES IN DISTANCE

FIELD OF THE INVENTION

The present invention relates to a sensor and a method for detecting changes in the distance between a first and a second location on the basis of optics.

BACKGROUND INFORMATION

It is believed that there are various methods for measuring changes in the distance between movable objects. For example, some methods may involve sensors, such as strain gauges, which are based on electrical methods. Changes in electric capacitance, as well as in magnetic flux are utilized when working with small changes in length. When employing optical methods to determine linear variations there is no need for an electrically conductive connection between the points whose change in distance is to be measured. There are interferometers for small and average distances of about 1 μm to 1 m, moiré systems, as well as transit-time measurements of light pulses. Interferometer systems may be very precise, but they may also be extremely sensitive mechanically. Also, their operation entails substantial outlay for adjustments. For that reason, it is believed that interferometer systems must be set up as substantially vibrationless systems, and they may not be simple to use, especially for detecting changes in the distance between moving objects. It is also believed that moiré systems are likewise precise, but, in a measuring range beyond a few centimeters, they may only be implemented at a considerable expense. Transit-time measurements of optical pulses and/or measurements of frequency shifts produced by the Doppler effect may only be accurate for large distances and may require costly measuring electronics.

The reference "Berry's phase analysis of polarization rotation in helicoidal fibers", by F. Wassmann and A. Ankiewicz,

Applied Optics, vol. 37, no. 18, June 1998, discusses a method for calculating the rotation of the polarization of light, which propagates through a helically wound optical fiber. The rotation of the polarization can be utilized for implementing an optical fiber sensor which can be used to determine the size of a displacement.

The reference "Two-dimensional HiBi fiber-optic coil strain sensor", by Y. Libo and A. Farhad, Acta Photonica Sinica, vol. 26, no. 7, July 1997, vol. 26, no. 7, pages 618-622, XP 000884999, discusses that with the aid of a wound optical fiber, to measure mechanical strains, the influence of the mechanical strain on the polarization state of the light is utilized, which propagates through the optical fiber.

The U.S. Patent No. 5,201,015 discusses a sensor for measuring mechanical strains with the aid of an optical fiber. The optical fiber has concentric windings. When a mechanical tensile stress is exerted on the sensor, the windings are elastically stretched, causing the peripheral path of the windings and, thus, also the optical path length of the light to increase in the optical fiber. The increase in the optical path length is utilized as a measure of the externally acting mechanical strain.

The U.S. Patent No. 4,389,090 discusses a device for producing specific polarization states of light in an optical fiber. At least one region of the optical fiber is formed as a winding or coil. The polarization state of the light can be adjusted and changed by varying the spatial orientation of the winding or coils, as well as by twisting the optical fiber.

SUMMARY OF THE INVENTION

An exemplary embodiment of the present invention is directed to providing a sensor for detecting changes in distance which is technically simple and inexpensive to implement, does not require any special mechanical stability, and which can be

used to precisely determine small positional changes. A further object of an exemplary method of the present invention is to provide a method for detecting changes in distance which is simple to implement.

Another exemplary embodiment of the present invention includes a sensor for detecting changes in the distance between a first and a second location having at least one substantially helically coiled optical fiber, which is able to be mechanically connected to at least one of the locations, and having a light transmitter and a detector for optical signals. In this context, the detecting device is able to generate an output signal, which is dependent upon the polarization state of the optical signal transmitted via the optical fiber. In addition, a reference optical fiber path is provided, which simulates the optical fiber and over which a second optical signal is transmitted, the optical signals transmitted over both paths being detected in a shared or in separate detecting devices so as to enable differences in the polarization state to be determined.

Another exemplary embodiment of the present invention includes a method for detecting distance variations between a first and a second location, where:

a) mechanically coupling at least one location to a substantially helically coiled optical fiber;

b) coupling an optical signal having a known polarization state into the optical fiber;

c) recording the optical signal transmitted over the connecting line in order to acquire information pertaining to its polarization state;

d) determining the change in distance from the information on the polarization state of the transmitted signal; and

e) comparing the polarization state of the optical signal following the transmission to that prior to the transmission and/or to a reference polarization state.

Another exemplary embodiment of the present invention involves

the polarization of light changing in helically wound optical fibers in response to a change in the helical parameters. The polarization of the light at the output of a simple, helically coiled, optical fiber line is sensitive to movement, in particular to accordion-like movements of the fiber. This dependency of the polarization on the form of the three-dimensional (or non-planar) curve of the fiber can be used directly to measure the form, e.g., the length of the accordion-like movements of the fiber windings. The distance between any two locations can be determined by connecting them using a movable, helically wound, elastic optical fiber line.

In another exemplary embodiment of the present invention, the form dependency of the polarization state at the output end of an optical fiber is at least in part due to the considerable dependency of the fiber's optical activity upon the exact form of its helical windings. In the first approximation, this effect is achromatic and does not result in any polarization mode dispersion. It is believed to be caused by one of the so-called optical Berry phases, the spin redirection phase. This Berry phase or geometric phase is a phase effect produced by the structure of the fiber's space curve and not by a difference in the optical path length, as is the case with the normal dynamic phase of light. Nevertheless, geometric phases lead to the same interference effects of the light as do normal dynamic phases.

The size or magnitude of the spin redirection phase in a helically wound fiber corresponds to the solid angle Ω that the k vector (k corresponds to the propagation constant β in the technical literature) wraps around on the sphere of the light-propagation orientations in the counter-clockwise direction when the light in the fiber is directed through a helical winding.

In another exemplary embodiment of the present invention, light is coupled with a defined polarization state into the

coiled optical fiber and the transmitted optical signal is detected so that inferences can be drawn with respect to its polarization state or its individual polarization components after propagating through the optical fibers. From the change in the parameters of the optical signal prior to and following the transmission, or from a comparison to a reference from a calibration measurement or a concurrent reference measurement, inferences can be drawn with respect to the form or the change in the form of the wound optical fiber and, thus, also with respect to changes in the distance between locations connected thereto.

In another exemplary embodiment, for example, polarized light can be coupled into the fiber, and its polarization state or the strength of a specific polarization component can be measured once it has propagated through the optical fiber using a polarimeter or a detector having a series-connected or upstream analyzer. From knowledge of the polarizations or of individual polarization components prior to and subsequent to the transmission, conclusions can be drawn with respect to the change in polarization caused by the form and, thus, with respect to the deformation of the coils.

In another exemplary embodiment of the present invention, if the transmission signal is compared to a reference, then precise knowledge of the polarization state prior to the transmission may not be necessary. It may be sufficient if a defined initial basic situation is always at hand. The reference is constituted, for example, of a series of measured values which were acquired during a calibration measurement using the optical fibers and which specify the output signal at specific distances between the first and second location. Alternatively, a reference signal can also be produced during the measurement in that a reference path, which may simulate the wound optical fiber, likewise receives a defined optical signal, and the two transmission signals are compared to one another. For this, they are either analyzed separately and/or

both intensities are compared to one another. The actual transmission signal can also be brought into interference with the reference transmission signal and subsequently can be detected in a shared detector.

Exemplary embodiments of the present invention can eliminate the need for specular surfaces or for a special mechanical stability of the system are virtually universally applicable. The launching the optical signal into the fiber should, in fact, be mechanically stable, but it can be set up separately from the system to be measured. In addition, without entailing substantial technical outlay, the sensor can be assembled from individual, inexpensive components.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a sensor having a helical optical fiber according to an exemplary embodiment of the present invention.

Figure 2 shows a helical optical fiber according to an exemplary embodiment of the present invention.

Figure 3 shows a sensor for measuring changes in the length of a telescope arm according to an exemplary embodiment of the present invention.

DETAILED DESCRIPTION

The lower part of Figure 1A shows a sensor according to an exemplary embodiment of the present invention having a helical optical fiber 1. The optical fiber has a fixed winding direction. In the case of an arbitrarily bent fiber, it may be sufficient when one winding direction predominates.

In addition, the optical fiber has a cladding which holds the fiber in its helically bent form and is capable of elastically following movements, in particular those along the longitudinal axis of the coil. For this, the coils, as such, can also be embedded in an elastic substrate material, for

example, in an elastic cylinder or the like.

The sensor also includes a light source 3, which may be a laser. Linearly polarized light emanating from light source 3 is launched into fiber coil 1. In the case that the light source does not emit fully polarized light, a polarizer P can be positioned at the fiber input end to produce the defined polarization state. At the output end of the fiber coil, the polarization state of the transmitted optical signal can be measured using a polarimeter 2. Alternatively, one can use a simple detector having a series-connected or upstream analyzer to measure the intensity of a defined polarization component.

Figure 1B schematically depicts a polarization ellipse to represent the polarization state of the light once it has propagated through the transmission route. X and y denote the vibration directions of the electric field vector. In the most general case, the field vector describes an ellipse having the main axes a and b, which is rotated by the angle φ in relation to the axes x and y.

Exemplary embodiments of the present invention involve that the orientation angle φ of the polarization ellipse at the output end of the fiber path being proportional to the so-called geometric phase introduced in the coil between the right-hand and left-hand circular component of the injected, linearly polarized light. Since the geometric phase changes with the coil shape, the orientation angle φ is a measure of and/or indicative of the coil shape. In this manner, the distance d between two points A1 and A2 can be measured on the coil and, thus, also the distance and/or the change in the distance between two locations rigidly connected by points A1 and A2.

Referring to Figure 2, the geometric spin redirection phase and, thus, the coil form can be determined quite simply. Each complete winding of the optical fiber on a cylinder Z of

radius r, having pitch St, for which the lead angle Θ is the same at the beginning A and end E of the winding, produces a rotation φ of the injected, linearly polarized light. The angle of rotation φ is given by

$$(1) \quad \varphi = \int_0^{2\pi} \left[1 - \cos\Theta(\Phi)\right] d\Phi$$

In this context, ϕ is the azimuth angle of cylinder Z; see Figure 2. For the case of a uniformly wound spiral, Θ is a constant, and one obtains:

$$(2) \quad \varphi(\Theta = const.) = 2\pi(1 - \cos) \text{ and } \cos\Theta = \frac{St}{L}$$

Thus, if one couples a linearly polarized light at angle α into the helix, then at the output end E, it has a polarization rotated by the angle φ thus $\alpha \pm \varphi$. The operational sign of angle of rotation φ depends on the helicity of the coil or screw. L is the length of the fiber helix. At this point, in response to a change in pitch St of the helix, the helix or pitch angle Θ and, thus, the polarization direction at fiber end E change. If a linear analyzer is installed at end E and then permits the light to strike a detector, then this registers an intensity I

$$(3) \quad I = I\cos^2[\gamma - (\alpha \pm \varphi)]$$

where γ is the orientation angle of the analyzer, and I_0 is the intensity of the linearly polarized light emerging from the fiber. The assumption here is that lossless conditions prevail and that the light in the fiber ideally remains linearly polarized.

For all other cases, I likewise depends on helix angle Θ and,

thus, on the distance between points AE, although in complicated fashion. The correlation (or relation) may be determined through calibration or by measuring the parameters of equation (1), as well the various losses. At the detector, one obtains a signal which is dependent upon distance St to be measured and can be brought into a suitable measuring range by parameters r, γ and α.

It is believed that it is not necessary that only one single winding of the fiber may be used as a distance indicator. In another exemplary embodiment of the present invention, many windings can be used, as in Figure 1, as well as non-whole numbers of windings. In the case of an integral number of turns or windings N between A and E and given the same helix angles at A and E, the angle of rotation φ may be calculated in accordance with equation (1), it being necessary to extend the upper integration limit to $2\pi N$. Given a number of turns N that is not whole and non-uniform windings, a calibration may be more advantageous than the calculation, which can no longer be performed in accordance with the simple equation (1).

To fabricate a uniform coil form having constant helix angles, spindles are mounted at points A and E at the beginning and end of the winding about which the fiber can rotate freely with respect to angle Θ. These spindles are disposed perpendicularly to the cylinder axis of the winding. The fiber is mounted on an elastic carrier, which has a pivot at A and E enabling it to rotate about the spindles. Since, in this case, the uniform helix adjusts itself automatically as a geodetic curve between points A and E on the cylinder, equation (3) can be applied for all pitches St of the helix, for whose formation the total length of the fiber suffices.

An optical fiber does not always retain the linear polarization; i.e., when it emerges from the fiber, the light is no longer polarized as it originally was upon its entry into the fiber. This effect is produced, on the one hand, by

deviations in the fiber core from circular symmetry and, on the other hand, by birefringence induced by the bending of the fiber. In so-called weakly birefringent fibers, which also feature a low polarization mode dispersion, an orientation distribution of the asymmetry of the fiber core is achieved in all spatial directions, for example, through rapid rotation of the preform when drawing the fibers. Therefore, fibers of this kind may be especially suited for manufacturing a length-measuring or distance-measuring sensor in accordance with the exemplary embodiments of the present invention.

To avoid stress-induced birefringence in the bent fiber, the bending radius of the fiber should not be too small. An estimation of the birefringence in bent fibers is given by L. Jeunhomme, Single-Mode Fiber Optics, N.Y. 1983, p. 60. It is believed to be optimal when the wound fiber helix has a phase lag of less than $\lambda/10$, λ being the operating wavelength. On the other hand, even higher strain birefringence values may not substantially interfere with the measuring principle, since, even in the case of elliptically polarized light at the output end of the fiber, the helix deformation causes changes in the orientation angle φ, which can be taken as a measure of the change in length. Large bending radii of the fibers can be achieved both by increasing the helix radius, as well as by enlarging the helical pitch.

A calibration of the sensor also includes changes in intensity in the detector at the fiber end, resulting from bending of the fiber in response to a change in the distance AE. A length measurement obtained by comparing the instantaneously measured values to values determined in a calibration measurement may be advantageous for the practical application of the sensor, since any influences on the polarization state of the light that are not caused by the change in the length of the wound optical fiber may be eliminated.

Figure 3 illustrates an exemplary embodiment of the present

invention. An elastic fiber carrier D, e.g., a steel, bronze or plastic wire, is provided with two mounting supports HA, HE, which can be fitted on spindles at A and E enabling them to freely rotate. The spindles at points A, E are connected to two tubes of a telescope arm, whose change in length needs to be measured. A helical optical fiber having one single winding is used, which is embedded in fiber carrier D.

Disposed upstream from holder HA is a light source LQ, which can also be mechanically connected to holder HA to assure stable coupling conditions. Light source LQ, which may produce linearly polarized light, is, e.g., a light-emitting diode or a semiconductor laser. The light is coupled via a lens L1 into the optical fiber, whose input end is positioned at holder HA. The fiber is secured on or in elastic fiber carrier D. In the case that the light source emits unpolarized light, linear polarizer PA must also be installed between the light source and the start of the fiber.

At the end E of the winding is holder HE, to which a lens L2 and the fixed or rotatable linear analyzer PE is secured. The lens images light from the fiber onto detector DE. Light source LQ and detector DE are connected via easily movable electric conductors to corresponding network and recording devices N and R, respectively. To avoid interference effects, the light source, detector, and glass fiber are obscured in light-proof manner from the outside world.

The exemplary embodiments of the present invention may be used in industrial applications to precisely detect changes in length and distance in a multiplicity of systems, such as in robot arms.

ABSTRACT OF THE DISCLOSURE

A sensor for detecting changes in the distance between a first and a second location, having at least one substantially helically coiled optical fiber, can be mechanically connected to at least one of the locations, and having a light transmitter and a detecting device for optical signals, the detecting device can generate an output signal, which is dependent upon the polarization state of the optical signal transmitted via the optical fiber. A method for detecting the changes in distance between a first and a second location includes the following: mechanically coupling at least one of the locations to a substantially helically coiled optical fiber; launching an optical signal having a known polarization state into the optical fiber; following transmission over the connecting line, detecting this so that information is obtained with respect to its polarization state; and determining the change in distance from this information.

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SENSOR AND METHOD FOR DETECTING CHANGES IN DISTANCE

Field of the Invention

The present invention relates to a sensor, as well as to a method for detecting changes in the distance between a first and a second location, on the basis of optics.

Background of the Invention

Many methods are known for measuring changes in the distance between movable objects. For example, one knows of sensors, such as strain gauges, which are based on electrical methods. Changes in electric capacitance, as well as in magnetic flux are utilized when working with small changes in length. The advantage of optical methods to determine linear variations is that there is no need for an electrically conductive connection between the points whose change in distance is to be measured. Customary are interferometers for small and average distances of about 1 μm to 1 m, moiré systems, as well as transit-time measurements of light pulses. Interferometer systems may be very precise, but they have the drawback of being mechanically extremely sensitive. Also, their operation entails substantial outlay for adjustments. For that reason, they must be set up as substantially vibrationless systems, so that they are not simple to use, especially for detecting changes in the distance moving objects. Moiré systems are likewise precise, but, in a measuring range beyond a few centimeters, they can only be implemented at a considerable expense; transit-time measurements of optical pulses and/or measurements of frequency shifts produced by the Doppler effect are only accurate for large distances and require costly measuring electronics.

Object of the Invention

The object of the present invention is, therefore, to provide a sensor for detecting changes in distance, which is technically simple and inexpensive to implement, does not require any special mechanical stability, and which can be used to precisely determine small positional changes. A further object of the present invention is to provide a method for detecting changes in distance which is simple to implement.

Summary of the Invention

The objective is achieved by a sensor for detecting changes in the distance between a first and a second location, having at least one substantially helically coiled optical fiber, which is able to be mechanically connected to at least one of the locations, and having a light transmitter and a detector for optical signals. In this context, the detecting device is able to generate an output signal, which is dependent upon the polarization state of the optical signal transmitted via the optical fiber.

Procedurally, the objective is achieved by a method for detecting distance variations between a first and a second location, having the following features:

a) mechanically coupling at least one location to a substantially helically coiled optical fiber;

b) coupling an optical signal having a known polarization state into the optical fiber;

c) recording the optical signal transmitted over the connecting line in order to acquire information pertaining to its polarization state;

d) determining the change in distance from the information on the polarization state of the transmitted signal.

Advantageous embodiments of the sensor and of the method are

characterized in the dependent claims 2 through 9 and 11 through 16, respectively.

The present invention is based on the principle of the polarization of light changing in helically wound optical fibers in response to a change in the helical parameters. The polarization of the light at the output of a simple, helically coiled, optical fiber line is sensitive to movement, in particular to accordion-like movements of the fiber. This dependency of the polarization on the form of the three-dimensional curve of the fiber can be used directly to measure the form, e.g. the length of the accordion of the fiber windings. Thus, the distance between any two locations can be determined by connecting them using a movable, helically wound, elastic optical fiber line.

The main reason for the form dependency of the polarization state at the output end of an optical fiber is the considerable dependency of the fiber's optical activity upon the exact form of its helical windings. In the first approximation, this effect is achromatic and does not result in any polarization mode dispersion. It is caused by one of the so-called optical Berry phases, the spin redirection phase. This Berry phase or geometric phase is a phase effect produced by the structure of the fiber's space curve and not by a difference in the optical path length, as is the case with the normal dynamic phase of light. Nevertheless, geometric phases lead to the same interference effects of the light as do normal dynamic phases.

The size of the spin redirection phase in a helically wound fiber is equivalent to the solid angle Ω that the k vector (k corresponds to the propagation constant β in the technical literature) wraps around on the sphere of the light-propagation orientations in the counter-clockwise direction when the light in the fiber is directed through a helical winding.

For that reason, it is important that light be coupled with a defined polarization state into the coiled optical fiber and that the transmitted optical signal be detected in a manner such that inferences can be drawn with respect to its polarization state or individual polarization components after propagating through the optical fibers. From the change in the parameters of the optical signal prior to and following the transmission, or from a comparison to a reference from a calibration measurement or a concurrent reference measurement, inferences can be drawn with respect to the form or the change in the form of the wound optical fiber and, thus, also with respect to changes in the distance between locations connected thereto.

For example, polarized light can be coupled into the fiber, and its polarization state or the strength of a specific polarization component can be measured, once it has propagated through the optical fiber, using a polarimeter or a detector having a series-connected analyzer. From knowledge of the polarizations or of individual polarization components prior to and subsequent to the transmission, conclusions can be drawn with respect to the change in polarization caused by the form and, thus, with respect to the deformation of the coils.

If the transmission signal is compared to a reference, then precise knowledge of the polarization state prior to the transmission is not absolutely necessary. It suffices if a defined initial basic situation is always at hand. The reference is constituted, for example, of a series of measured values which were acquired during a calibration measurement using the optical fibers and which specify the output signal at specific distances between the first and second location. Alternatively, a reference signal can also be produced during the measurement in that a reference path, which preferably simulates the wound optical fiber, likewise receives a defined optical signal, and the two transmission signals are compared to one another. For this, they are either analyzed separately

and both intensities are compared to one another. The actual transmission signal can also be brought into interference, however, with the reference transmission signal and subsequently be detected in a shared detector.

The benefits provided by the present invention of eliminating the need for specular surfaces or for a special mechanical stability of the system, are virtually universally applicable. The launching the optical signal into the fiber should, in fact, be mechanically stable, but it can be set up separately from the system to be measured. In addition, without entailing substantial technical outlay, the sensor can be assembled from individual, inexpensive components.

Brief description of the drawing, whose figures show:

Figure 1 a sensor according to the present invention having a helical optical fiber;

Figure 2 a detail of a helical optical fiber;

Figure 3 a sensor according to the present invention for measuring changes in the length of a telescope arm.

Ways for Executing the Present Invention

The lower part of Figure 1A shows a sensor according to the present invention having a helical optical fiber 1. Here, the optical fiber has a fixed winding direction. Generally, in the case of an arbitrarily bent fiber, it suffices when one winding direction predominates.

In addition, the optical fiber has a cladding which holds the fiber in its helically bent form and is capable of elastically following movements, in particular those along the longitudinal axis of the coil. For this, the coils, as such, can also be embedded in an elastic substrate material, for example in an elastic cylinder or the like.

The sensor also includes a light source 3, which is preferably

a laser. Linearly polarized light emanating from light source 3 is launched into fiber coil 1. In the case that the light source does not emit fully polarized light, a polarizer P is positioned at the fiber input end to produce the defined polarization state. At the output end of the fiber coil, the polarization state of the transmitted optical signal is measured using a polarimeter 2. Alternatively, one can use a simple detector having a series-connected analyzer to measure the intensity of a defined polarization component.

Figure 1B schematically depicts a polarization ellipse to represent the polarization state of the light once it has propagated through the transmission route. X and y denote the vibration directions of the electric field vector. In the most general case, the field vector describes an ellipse having the main axes a and b, which is rotated by the angle φ in relation to the axes x and y.

The present invention utilizes that the orientation angle φ of the polarization ellipse at the output end of the fiber path is proportional to the so-called geometric phase introduced in the coil between the right-hand and left-hand circular component of the injected, linearly polarized light. Since the geometric phase changes with the coil shape, the orientation angle φ is a measure of the coil shape. In this manner, the distance d between two points A1 and A2 can be measured on the coil and, thus, also the distance and/or the change in the distance between two locations rigidly connected by points A1 and A2.

In the special cases described in the following and elucidated on the basis of Figure 2, the geometric spin redirection phase and, thus, the coil form can be determined quite simply. Each complete winding of the optical fiber on a cylinder Z of radius r, having pitch St, for which the lead angle Θ is the same at the beginning A and end E of the winding, produces a rotation φ of the injected, linearly polarized light. The

angle of rotation φ is given by

$$(1) \quad \varphi = \int_0^{2\pi} [1 - \cos\Theta(\Phi)] d\Phi$$

In this context, ϕ is the azimuth angle of cylinder Z; see Figure 2. For the case of a uniformly wound spiral, Θ is a constant, and one obtains:

$$(2) \quad \varphi(\Theta = const.) = 2\pi(1 - \cos) \text{ and } \cos\Theta = \frac{\mathrm{St}}{\mathrm{L}}$$

Thus, if one couples A linearly polarized light at angle α into the helix, then at the end E, it has a polarization rotated by the angle φ thus $\alpha \pm \varphi$. The operational sign of angle of rotation φ depends on the helicity of the coil. L is the length of the fiber helix. At this point, in response to a change in pitch ST of the helix, the helix angle Θ and, thus, the polarization direction at fiber end E change. If one installs a linear analyzer at end E and then permits the light to strike a detector, then this registers an intensity I

$$(3) \quad I = I\cos^2[\gamma - (\alpha \pm \varphi)]$$

when γ is the orientation angle of the analyzer, and I_0 is the intensity of the linearly polarized light emerging from the fiber. The assumption here is that lossless conditions prevail and that the light in the fiber ideally remains linearly polarized.

For all other cases, I likewise depends on helix angle Θ and, thus, on the distance between points AE, although in complicated fashion. The correlation is preferably determined through calibration or by measuring the parameters of equation (1), as well the various losses. At the detector, one obtains

a signal which is dependent upon distance St to be measured and can be brought into a suitable measuring range by parameters r, γ and α.

It is not necessary that only one single winding of the fiber be used as a distance indicator. It is likewise possible to use many windings, as in Figure 1, as well as non-whole numbers of windings. In the case of an integral number of turns N between A and E and given the same helix angles at A and E, it is possible to calculate the angle of rotation φ in accordance with equation (1), it being necessary to extend the upper integration limit to $2\pi N$. Given a number of turns N that is not whole and non-uniform windings, a calibration is more advantageous than the calculation, which can no longer be performed in accordance with the simple equation (1).

To fabricate a uniform coil form having constant helix angles, spindles are mounted at points A and E at the beginning and end of the winding about which the fiber can rotate freely with respect to angle Θ. These spindles are disposed perpendicularly to the cylinder axis of the winding. The fiber is mounted on an elastic carrier, which has a pivot at A and E enabling it to rotate about the spindles. Since, in this case, the uniform helix adjusts itself automatically as a geodetic curve between points A and E on the cylinder, equation (3) can be applied for all pitches St of the helix, for whose formation the total length of the fiber suffices.

Generally, an optical fiber does not retain the (linear) polarization; i.e., when it emerges from the fiber, the light is no longer polarized as it originally was upon its entry into the fiber. This effect is produced, on the one hand, by deviations in the fiber core from circular symmetry and, on the other hand, by birefringence induced by the bending of the fiber. In so-called weakly birefringent fibers, which also feature a low polarization mode dispersion, an orientation distribution of the asymmetry of the fiber core is achieved in

all spatial directions, for example through rapid rotation of the preform when drawing the fibers. Therefore, fibers of this kind are especially suited for manufacturing a length-measuring sensor sensor in accordance with the present invention.

To avoid stress-induced birefringence in the bent fiber, the bending radius of the fiber should not be too small. An estimation of the birefringence in bent fibers is given by L. Jeunhomme, Single-Mode Fiber Optics, N.Y. 1983, p. 60. It is ideal when the wound fiber helix has a phase lag of less than $\lambda/10$, λ being the operating wavelength. On the other hand, even higher strain birefringence values do not substantially interfere with the measuring principle, since, even in the case of elliptically polarized light at the output end of the fiber, the helix deformation causes changes in the orientation angle φ, which can be taken as a measure of the change in length. Large bending radii of the fibers can be achieved both by increasing the helix radius, as well as by enlarging the helical pitch.

A calibration of the sensor also includes changes in intensity in the detector at the fiber end, resulting from bending of the fiber in response to a change in the distance AE. A length measurement obtained by comparing the instantaneously measured values to values determined in a calibration measurement is advantageous for the practical application of the sensor, since it makes it possible to eliminate any influences on the polarization state of the light that are not caused by the change in the length of the wound optical fiber.

Figure 3 illustrates one practical specific embodiment of the present invention. An elastic fiber carrier D, for example a steel, bronze or plastic wire, is provided with two mounting supports HA, HE, which can be fitted on spindles at A and E enabling them to freely rotate. In the described example, the spindles at points A, E are connected to two tubes of a

telescope arm, whose change in length needs to be measured. In the described example, a helical optical fiber having one single winding is used, which is embedded in fiber carrier D.

Disposed upstream from holder HA is a light source LQ, which can also be mechanically connected to holder HA to assure stable coupling conditions. Light source LQ, which preferably produces linearly polarized light, is, for example, a light-emitting diode or a semiconductor laser. The light is coupled via a lens L1 into the optical fiber, whose input end is positioned at holder HA. The fiber is secured on or in elastic fiber carrier D. In the case that the light source emits unpolarized light, linear polarizer PA must also be installed between the light source and the start of the fiber.

At the end E of the winding is holder HE, to which a lens L2 and the fixed or rotatable linear analyzer PE is secured. The lens images light from the fiber onto detector DE. Light source LQ and detector DE are connected via easily movable electric conductors to corresponding network and recording devices N and R, respectively. To avoid interference effects, the light source, detector, and glass fiber are obscured in light-proof manner from the outside world.

Industrial Applicability

The present invention can be advantageously used in industrial applications to precisely detect changes in length and distance in a multiplicity of systems, such as in robot arms.

What is claimed is:

1. A sensor for detecting changes in the distance between a first and a second location, having at least one substantially helically coiled optical fiber, which is able to be mechanically connected to at least one of the locations, and having a light transmitter and a detecting device for optical signals, the detecting device being able to generate an output signal, which is dependent upon the polarization state of the optical signal transmitted via the optical fiber.

2. The sensor as recited in Claim 1, wherein the detecting device is a polarimeter or a detector having a series-connected analyzer.

3. The sensor as recited in Claim 1 or 2, wherein the optical fiber is flexible in the helix direction and is capable of following to changes in distance between the first and the second location.

4. The sensor as recited in one of Claims 1 through 3, wherein the optical fiber is joined to an elastic carrier material, which, in response to mechanical loading of the optical fiber, permits a change in the form and, in response to the lack of a mechanical load, retains the optical fiber in its initial curved form.

5. The sensor as recited in one of the preceding claims, wherein the optical fiber is wound around at least one elongated carrier element, preferably a cylinder, the carrier element preferably being flexible.

6. The sensor as recited in one of the preceding claims, wherein the optical fiber is secured to the carrier element in such a way that it is movable in its wound form, but remains stabilized on the carrier element.

7. The sensor as recited in one of the preceding claims, wherein in the case of the optical fiber, one winding direction predominates; the optical fiber preferably has only one winding direction.

8. The sensor as recited in one of the preceding claims, wherein the light source produces linearly polarized light, and/or a linear polarizer is situated at the input end of the optical fiber.

9. The sensor as recited in one of the preceding claims, wherein a reference optical fiber path is provided, which simulates the optical fiber and over which and a second optical signal is transmitted, the optical signals transmitted over both paths being sensed in a common or in separate detecting devices, such that differences in the polarization state can be determined.

10. A method for detecting changes in the distance between a first and a second location comprising the following features:
a) mechanically coupling at least one of the locations to a substantially helically coiled optical fiber;
b) launching an optical signal having a known polarization state into the optical fiber;
c) sensing the optical signal transmitted over the connecting line in order to acquire information pertaining to its polarization state;
d) determining the change in distance from the information on the polarization state of the transmitted signal.

11. The method as recited in Claim 10, wherein the change in distance is determined by comparing the detected signal and, as the case may be, individual parameters of the detected signal to values determined in a calibration measurement which correspond to a specific distance.

12. The method as recited in Claim 10, wherein the change in distance is calculated from the detected signal and, as the case may be, from individual parameters of the detected signal and from the form of the three-dimensional curve of the optical fiber.

13. The method as recited in one of the Claims 10 through 12, wherein the polarization state of the optical signal following the transmission is compared to that prior to the transmission and/or to a reference polarization state.

14. The method as recited in Claim 13, wherein the reference polarization state is the polarization state of the optical signal measured following its propagation through the communication link in the mechanical idle state.

15. The method as recited in one of Claims 10 through 14, wherein the optical signal is detected, together with a reference signal.

16. The method as recited in one of the Claims 10 through 14, wherein linearly polarized light is launched into the optical fiber, and light having a defined linear polarization is detected.

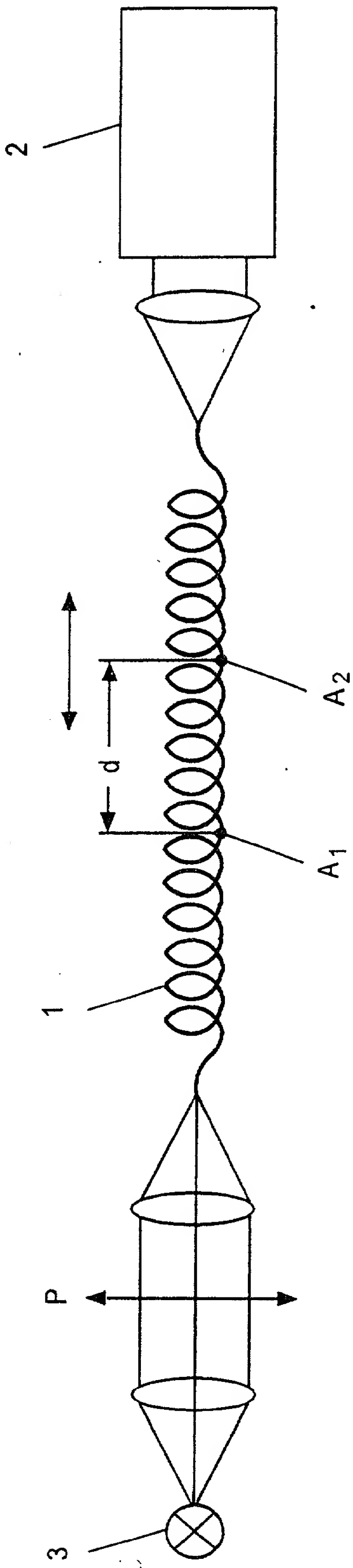

Fig. 1A

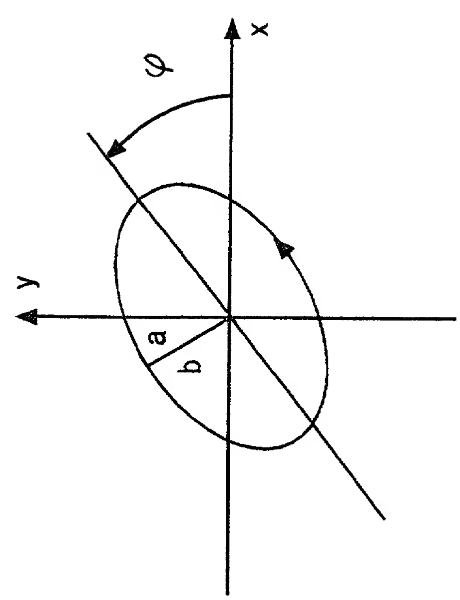

Fig. 1B

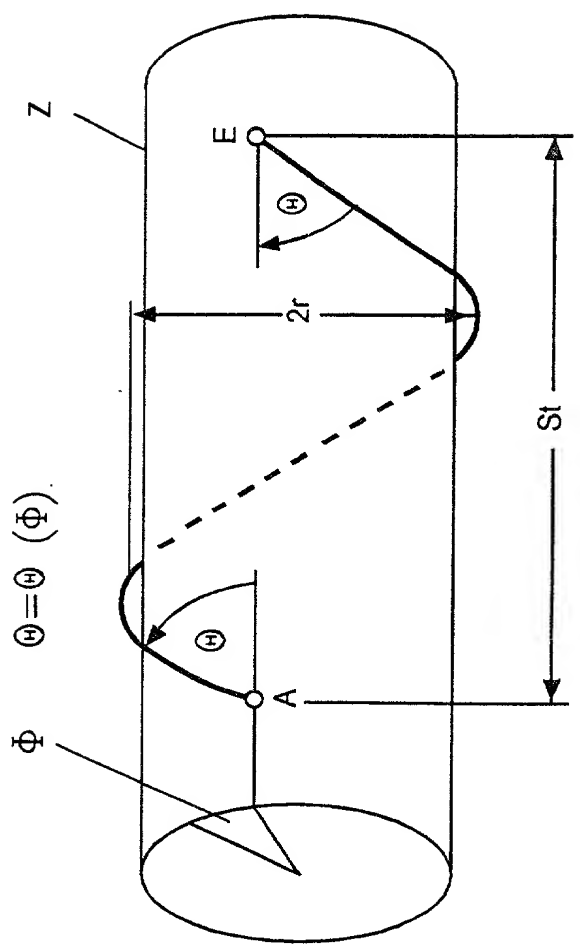

Fig. 2

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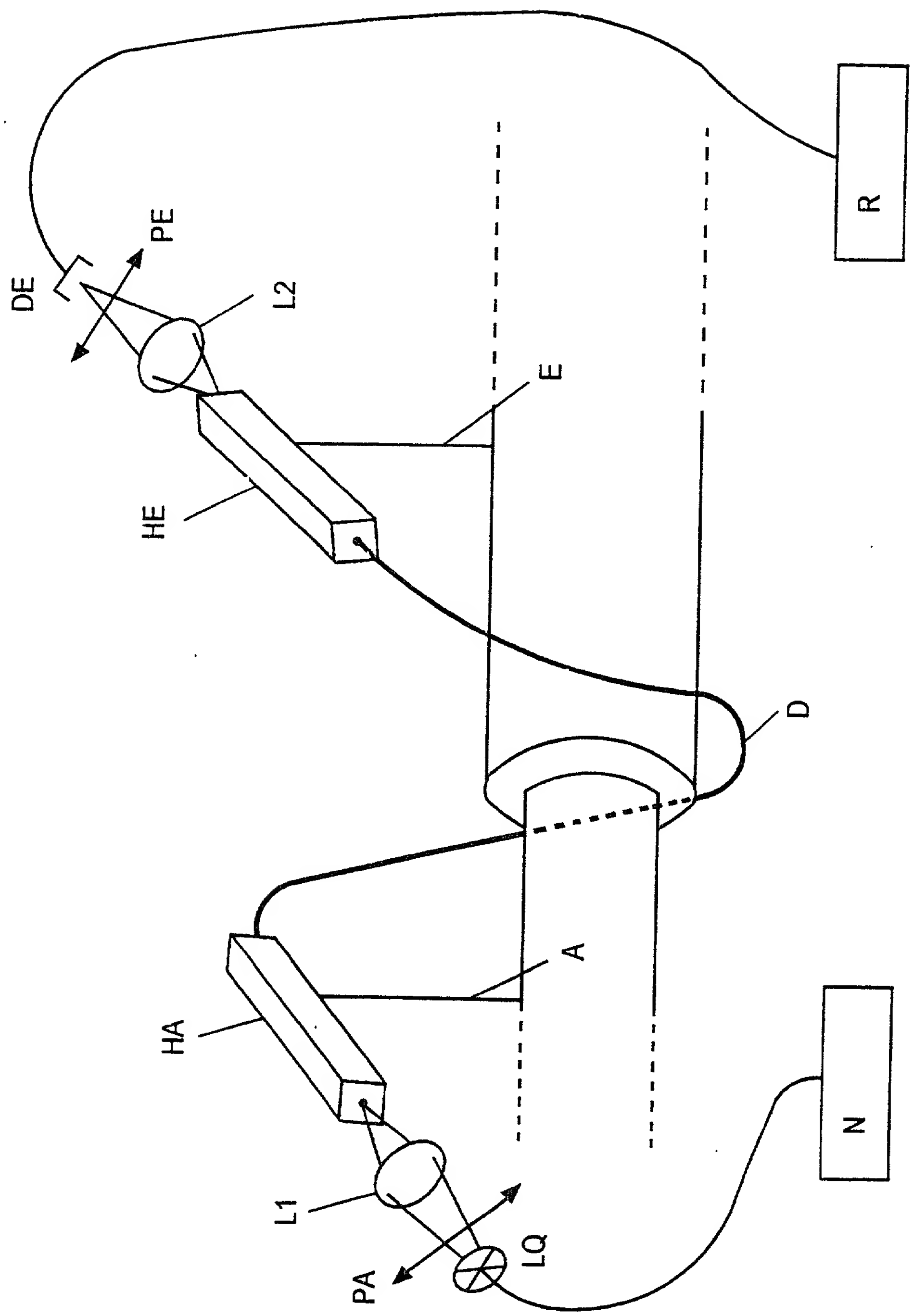

Fig. 3

2345/158

DECLARATION AND POWER OF ATTORNEY

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name.

I believe I am an original, first and joint inventor of the subject matter which is claimed and for which a patent is sought on the invention entitled **SENSOR AND METHOD FOR DETECTING CHANGES IN DISTANCE**, the specification of which was filed as International Application No. PCT/EP99/09845 on 9th of December 1999 and filed as U.S. application on July 30, 2001 having U.S. Serial No. 09/890,394 for Letters Patent in the U.S.P.T.O.

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims.

I acknowledge the duty to disclose information which is material to the examination of this application in accordance with Title 37, Code of Federal Regulations, § 1.56(a).

I hereby claim foreign priority benefits under Title 35, United States Code, § 119 of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application(s) for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

PRIOR FOREIGN APPLICATION(S)

Number	Country Filed	Day/Month/Year	Priority Claimed Under 35 USC 119
199 034 47.8	Fed. Rep. of Germany	29 January 1999	Yes

Express Mail No. EL243098634US

3

And I hereby appoint Richard L. Mayer (Reg. No. 22,490), Gerard A. Messina (Reg. No. 35,952) and Linda M. Shudy (Reg. No. 47,084) my attorneys with full power of substitution and revocation, to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith.

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful and false statements may jeopardize the validity of the application or any patent issued thereon.

1-00

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